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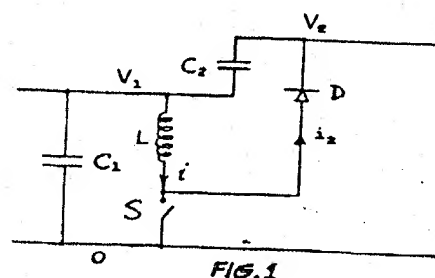
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(54) Power supply systems for inductive elements.

(57) In a power supply system, an inductance L is connected between a rail at a voltage V_1 and a rail at earth through a switch S . When the switch is opened, a current i_2 flowing from the inductance L is directed to a third rail through a diode D , voltage on the third rail rising to V_2 . The system may function as a dc to dc converter with an output voltage between the V_1 rail and the V_2 rail equal to $V_2 - V_1$. The system may alternatively be used in, for example, a reluctance motor drive, in which case a further inductance with associated switch and diode is included in the circuit in inverse configuration to prevent excessive voltage rise on the third rail.



5 This invention relates to power supply systems for feeding inductive elements and in particular to power supply systems for feeding switched inductive windings such as the phase windings of a switched variable reluctance motor. A motor of this kind, to which the present invention may be applied, is disclosed in our co-pending Patent Application entitled "Variable Speed Variable Reluctance Electrical Machines".

10 The invention also relates to power systems in general, and in particular to certain configurations of power systems serving as dc (direct current) to dc converters.

15 In a variable reluctance motor provided with a unipolar drive, current may be switched into the phase windings by electronic devices under PWM control. In considering the electrical behaviour of the power supply circuit for the phase windings, the windings may be regarded as inductors under certain
20 operating conditions, in that their response to current flowing through them under such circumstances is largely determined by their inductance rather than by their resistance. When the switch for a particular winding is closed, current flows through the inductor in question, which may then be connected between a supply rail and ground. Energy is thus stored in the

magnetic field of the winding, the amount of this energy being $\frac{1}{2}i^2L$, where i is the current and L is the inductance of the winding. When the switch opens again, this energy stored in the magnetic field has either to be dissipated or, preferably, returned regeneratively to the supply. In a particular supply arrangement for reluctance motors, the switched end of the winding is also connected to a second supply rail through a normally reverse biased diode. Thus in this arrangement, winding current transfers to the diode after the switch has opened and decays if the second supply rail has the appropriate polarity. However it is frequently the case that such supply rails are unable to regenerate energy, with the possible result that the voltage of the second supply rail may rise to a destructive level unless an equal or greater current is drawn from it than that being supplied by the phase winding. Dealing with or disposing of this inductively stored energy is thus a considerable problem in the application of variable reluctance motors, especially in situations where they are required to operate at low rotational speeds.

A twin-rail power supply with an equal number of motor phases connected to the positive and negative rails may be adequate for reluctance motors operating in a continuously-rotating motoring mode only, with non-usable inductively stored winding energy being returned to the complementary rail for use in the phases connected thereto, but this is not necessarily the case in a motor required to provide torque at zero speed in order to hold a load, where the current of the driving phases, less losses, may be transferred continuously between the rails and may pump up a supply capacitor located, for example, between the second rail and earth. At certain rotor positions the effects of two phases will cancel, and between these points, peaks of upward and downward current transfer will be reached. Thus, the effect at zero speed is to unbalance the rails. On the other hand, in a reluctance motor rotating at speed and

acting to decelerate an inertial load or otherwise regenerate energy, the effect will be to pump up both supplies.

5 This second-mentioned effect is the same as that which exists in any conventional servodrive, and since the total energy involved in a typical duty cycle is not great, it may be dealt with by burning it off in a dump resistor disposed between the rails. As a rule of thumb, the dump resistor is usually sized to intermittently draw a current equal to the continuous rating of one axis in a DC drive (e.g. 20A or 40A). The first effect, 10 i.e. that at zero speed, is not seen in DC servodrives with a single rail supply. One solution to the problem is to switch the reluctance motor phases at both top and bottom but this doubles the number of main devices.

15 A second technique to regenerate phase energy into the main supply is to use special bifilar windings in the motor. While this may seem attractive from many points of view there are also serious problems with this approach, as noted below, since the number of connections to the motor is doubled. In particular, to allow for worst case duties, the secondary 20 winding would need to have virtually the same cross-section as the primary, thus greatly reducing the utilization of winding area and motor rating. In addition, in a bifilar winding, two closely coupled coils are connected to opposite supply rails and may have very high potential differences between them, 25 leading to unreliable operation and breakdown. While appropriate for low voltage battery operation, this could cause serious problems with supplies over 100 V. Also as a main transistor switches off and a secondary winding takes over current conduction, very fast current rises and falls would 30 take place in the leads to the winding. This, along with poor coupling between primary and secondary windings, could give rise to severe electromagnetic noise radiation. Bifilar windings may thus be seen to be appropriate only when the drive

electronics are mounted close to the motor.

5 Since in virtually every application a servomotor requires to hold the friction torque of the mechanism it is driving when at stall, and stall current can be up to half the motor continuous rating, and since also in many applications, the motor will be holding an uncounterbalanced load, the provision of some effective and economical means of transferring energy away from a supply undergoing pump-up is regarded as a necessary feature of at least servomotor drives.

10 It may be argued that in large multi-axis systems, conditions at large should cancel out, so as to make the problem a relatively minor one. On the other hand, a solution to the unbalance problem must be available for implementation in systems where it is required. A very crude solution would be to have
15 individual dump resistors on the rails to burn off the unbalance. However, since this might involve burning off the rated motor current continuously, it would hardly be acceptable.

20 According to the invention, there is provided a power supply system for at least one inductive element, said system having first and second rails energisable at differing potentials, between which said element is switchingly connectible and a third rail to which current flow to or from said element may be directed when the connection of said element between the first
25 and second rails is broken, a further inductive element being switchingly connectible between said third rail and one of said first and second rails, and the system also comprising means for connecting said further element between said third rail and said one of the first and second rails when the voltage on the
30 third rail is equal to or greater than a predetermined value and means for facilitating current flow between the further inductive element and the other of said first and second rails when the connection of said further element between the third

rail and said one of the first and second rails is broken.

5 An inductive element is to be regarded as any component of the system having inductance as the primary parameter determining its electrical behaviour. Thus when the current flows through an inductive element as herein defined, it is inductance rather than resistance or any other measure of its electrical characteristics that determines its behaviour. The or each inductive element connectible between the first and second supply rails of the system may be a magnetising or exciting winding of a variable reluctance motor.

10 In the power supply system according to the invention, a resistive element may also be switchingly connectible between said third rail and said one of the first and second rails, and the system may comprise means for connecting said resistive element between said third rail and said one of the first and second rails when the voltage between said third rail and said one of the first and second rails is equal to or greater than a predetermined value.

20 Current flowing from the or each inductive element connectible between the first and second rails of the system is preferably directed to the third rail by a diode, while the current flowing from the further inductive element may be similarly directed to said other of the first and second rails by a further diode. The inductance of said further inductive element is suitably selected to be substantially the same as that of the or each inductive element connectible between the first and second rails. The connection of each of the elements connectible between supply rails of the system most suitably takes place under the control of proportional-integral-differential type control means or systems in which an excess voltage represents an error signal, in dependence on the value of which, switches connecting the inductive element across the rails may be opened or closed as appropriate under PWM control.

5 In another aspect, the invention provides a power supply system having first and second rails energisable at differing potentials between which an inductive element is switchingly connectible and a third rail to which current flow to or from said inductive element may be directed when the connection of said element between the first and second rails is broken.

10 In a particular configuration of system according to this aspect of the invention, a dc (direct current) to dc converter may be provided comprising a system having first and second rails energisable at differing potentials between which an inductive element is switchingly connectible and a third rail to which current flowing from said inductive element may be directed when the connection of said element between the first and second rails is broken.

15 A dc voltage may be applied across the first and second rails and a dc load placed across the first and third rails. Opening and closing of the switch connecting the inductive element between the first and second rails results in a voltage being built up on the third rail, and the voltage across the dc load
20 is represented by the difference between the respective voltages of the first rail and third rail relative to the second rail.

Embodiments of the invention will now be described having regard to the accompanying drawings in which:

25 Figure 1 is a schematic diagram of a unipolar drive for a switched variable reluctance motor,

Figure 2 is a schematic diagram of a power supply system according to the present invention,

30 Figure 3 is a schematic diagram of a further configuration of power supply system according to the present invention, Figures 4 and 5 show respectively, two embodiments of dc converter incorporating features of the present invention,

Figures 6 and 7 show in schematic and comparative form only, the operation of converters according to Figures 4 or 5 under alternative regimes,

5 Figure 8 shows a system according to the invention including two inductive elements,

Figure 9 shows a converter according to the invention providing for isolation between input and output, and

Figure 10 shows typical waveforms for the system of Figure 9 under full load conditions.

10 As shown in Figure 1, a phase winding L of a variable reluctance motor is connected between a first rail at a voltage V_1 , and a second rail at earth 0 through a switch S. When the switch S is closed, a current indicated by i builds up through the inductor L. When the switch is opened again, the
15 current will transfer to the diode D as i_2 . If the rail to which this current flows through the diode D is unable to regenerate the returned energy, the voltage on the capacitor C_2 between the first and third rails will rise, with possibly destructive results, if no precautionary action is taken.

20 As shown in Figure 2, the four phase windings 1, 2, 3 and 4 of a four-phase reluctance motor are fed from a single-ended power supply consisting of a negative rail 5 and a ground rail 6, through respective switches 7, 8, 9 and 10. In order to dispose of the inductive energy stored in the phase windings, which behave as inductive elements as herein defined to return
25 energy to the power supply system on phase switch-off, diodes 11, 12, 13 and 14 direct the returned energy to an upper rail 15, which is not tied to any voltage and serves merely as a means for recirculating and disposing of returned energy. A
30 dummy phase winding 16 in the form of an inductive coil of substantially the same value of inductance as each of the phase windings 1 to 4 bridges between the upper floating rail 15 and the ground rail 6. The floating rail is connected through the

5 dummy winding 16 to the ground rail by a switch 17, similar to
the switches 7 to 10 of the main motor phase windings. In
order to take away returned inductive energy from the element
16 when the switch 17 is opened, a diode 18 is connected
10 between the inductive element 16 and the negative rail for the
same direction of current flow as the diodes associated with
the phase windings proper. A dump resistor 19 between the
floating rail and the ground rail is switched in or out by
switch 20 and serves for disposal of returned energy during
regeneration, when all motor phases are active.

15 The system incorporating the features of the invention as
described above recirculates any unbalanced transfer of energy
from the negative rail during unbalanced operating conditions,
such as may prevail when a servomotor is at standstill, so that
20 pump-up or excessive build-up of voltage on that rail may be
avoided. A logic circuit associated with the power system
detects the build-up of voltage and functions to operate switch
17 at appropriate intervals so that it recirculates such energy
in a manner complementary to the way in which the active phase
winding or windings remove it from the negative rail, and
normal voltage conditions may thereby be maintained in the
power supply system. This detection circuit will normally be a
proportional/integral/differential type control system with
25 excess auxiliary power supply voltage as its error signal. The
dump resistor 19 will be activated by switch 20 when operation
of the anti-pump-up circuit as described above causes the main
power supply to build up excess voltage. In one implement-
ation, excess main rail voltage inhibits the operation of the
dummy winding 16 and the dump circuit is activated when the
30 auxiliary rail voltage passes a preset threshold.

In the three-rail system of Figure 3, a substantially similar
arrangement is provided but the upper rail 15 is in this
instance a positive rail at +V. Two dummy windings 16a and 16b

are then necessary to link between the positive 15 and negative 5 rails respectively and the ground rail 6, since in this instance the negative rail 5 is also subject to being pumped-up by the positive rail 15. Similarly, each dummy winding has an associated switch 17a, 17b and a diode 18a and 18b respectively. Two dump resistors 19a and 19b are also provided for disposal of energy during regeneration, and are switched by respective switches 20a, 20b.

Operation of this system is essentially similar to that of the first arrangement, the appropriate dummy winding being switched depending on which of the rails is being "pumped-up" under standstill or unbalanced conditions of phase winding energisation. The scheme of Figure 3 substantially equates to a back-to-back positioning of two circuits as illustrated in Figure 2.

Referring again to Figure 1, it will be seen that the action of the circuit shown is one of transferring energy from a supply rail at a potential V_1 to a supply rail at a potential V_2 , using only a single inductive element, a switch and a diode. Energy may be drawn from capacitor C_2 at a potential of $V_2 - V_1$. According to the second aspect of the invention, this circuit forms the basis of a dc to dc converter of an advantageous nature. The magnitude of the voltage V_2 is controlled by the on-time and switching frequency of switch S. The longer the switch is closed, the higher the current that builds up in the inductor and the greater the energy transfer to the second rail. Similarly, the more frequently the switch is closed, the greater the energy transfer. Thus the switch may operate in a PWM mode, with the on-off time varying, or a chopper may be used in which the on-time is fixed but the frequency of switching is varied. For a changing load on the second rail, a feedback loop controlling one of the variables of the system may be needed to stabilise the voltage.

Two examples of applications of this aspect of the invention are illustrated in Figures 4 and 5. In each case a 24v battery supply V_1 is stepped up to drive a 48v (V_2-V_1) load. The configuration of Figure 4 gives a positive output voltage, while that of Figure 5 gives a negative output voltage.

Figures 6 and 7 show the inter-relationship between the switching frequency and its duration and the currents i_1 and i_2 of Figures 4 and 5 for a small V_2-V_1 (Figure 6) and for a larger value of this voltage (Figure 7). The diagrams are schematic and comparative only and are not intended to indicate any specific values of current or time.

Two or more inductive elements may be combined in a power supply system or converter according to the invention in order to increase the power rating. An arrangement having two inductors is shown in Figure 8. In such a circuit, the switching of S_1 and S_2 may be staggered to improve the uniformity of the combined current $i_2 + i_4$.

Electrical isolation between input and output is a frequent requirement for dc to dc converters. This may be achieved in the arrangement shown in Figure 9, in which each inductor L is replaced by an element or device wound with two separate but closely coupled coils, designated L_{11} , L_{12} , L_{21} , L_{22} and L_{31} , L_{32} in the three phase circuit of Figure 9. These devices are to be distinguished from transformers, in that they may include an airgap in the magnetic circuit to provide a relatively low and well-defined magnetizing inductance, or alternatively, that they achieve this latter result by any other appropriate means.

Typical waveforms for the three-phase circuit of Figure 9 are depicted in Figure 10, for full load conditions in the case where $V_2 = 2V_1$ and the inductor windings have a 1:2 turns

ratio. Suitable waveforms for conditions other than full load are achieved by controlling the ON time of the switches in a chopping or PWM mode.

5 Thus according to a further aspect of the invention, the power supply system may include a plurality of said inductive elements connectible between said first and third rails. The
10 or each said inductive element may have first and second coils, said first coil being connectible between said first and second rails and being isolated from said second coil, and said current flowing from said second coil when said connection is broken.

CLAIMS

1. A power supply system having first (5) and second (6) rails energisable at differing potentials, between which an inductive element (1, 2, 3, 4) is switchingly connectible, and a third rail (15) to which current flow to or from said inductive element (1, 2, 3, 4) may be directed when the connection of said element (1, 2, 3, 4) between the first (5) and second (6) rails is broken.

2. A dc (direct current) to dc converter comprising a power supply system according to claim 1.

3. A power supply system for at least one inductive element (1, 2, 3, 4), said system having first (5, 15) and second (6) rails energisable at differing potentials, between which said element (1, 2, 3, 4) is switchingly connectible, and a third rail (5, 15) to which current flow to or from said element (1, 2, 3, 4) may be directed when the connection of said element (1, 2, 3, 4) between the first (5, 15) and second (6) rails is broken, a further inductive element (16, 16a, 16b) being switchingly connectible between said third rail (15, 5) and one (6) of said first (5, 15) and second (6) rails, and the system also comprising means (17) for connecting said further element (16, 16a, 16b) between said third rail (15, 5) and said one (6) of the first (5, 15) and second (6) rails when the voltage on the third rail (15, 5) is equal to or greater than a predetermined value and means for facilitating said current flow between the further inductive element (16, 16a, 16b) and the other (5, 15) of said first (5, 15) and second (6) rails when the connection of said further element (16, 16a, 16b) between the third rail (15, 5) and said one (6) of the first (5, 15) and second (6) rails is broken.

4. A power supply system according to claim 3, wherein a resistive element (19, 19a, 19b) is also switchingly connectible between said third rail (15, 5) and said one (6) of the first (5, 15) and second (6) rails, and the system
5 comprises means (20, 20a, 20b) for connecting said resistive element (19, 19a, 19b) between said third rail (15, 5) and said one (6) of the first (5, 15) and second (6) rails when the voltage between said third rail (15, 5) and said one of the first (5, 15) and second (6) rails is equal to or greater than
10 a predetermined value.

5. A power supply system according to claim 1, comprising a plurality of said inductive elements connectible between said first and third rails.

6. A power supply system according to claim 1, wherein said
15 inductive element has first and second coils, said first coil being connectible between said first and second rails and being isolated from said second coil, and said current flowing from said second coil when said connection is broken.

7. A dc to dc converter comprising a power supply system
20 according to claim 5 or claim 6.

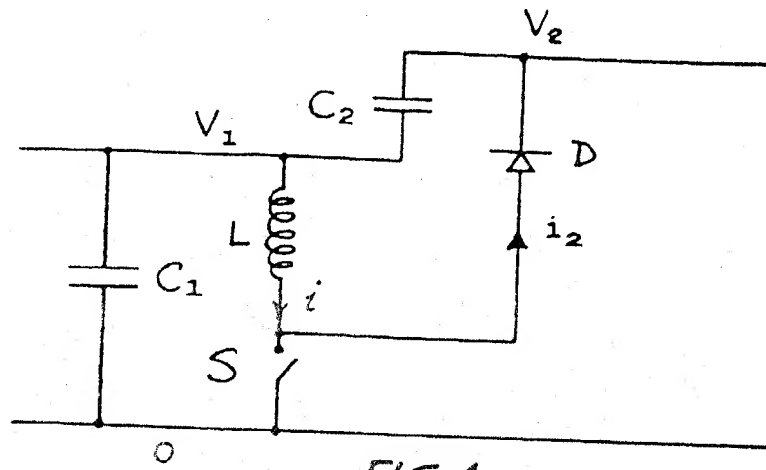


FIG. 1

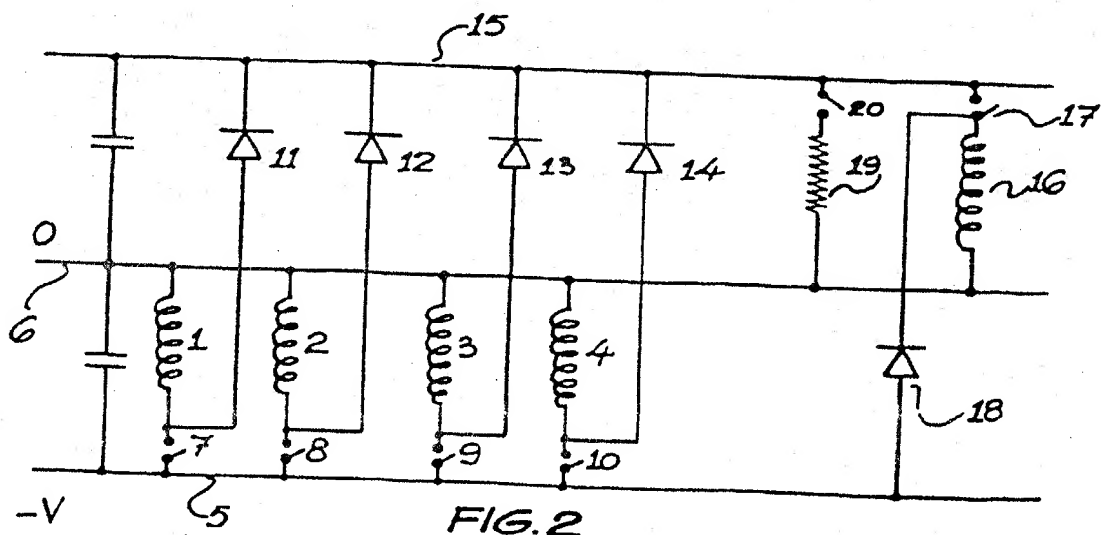


FIG. 2

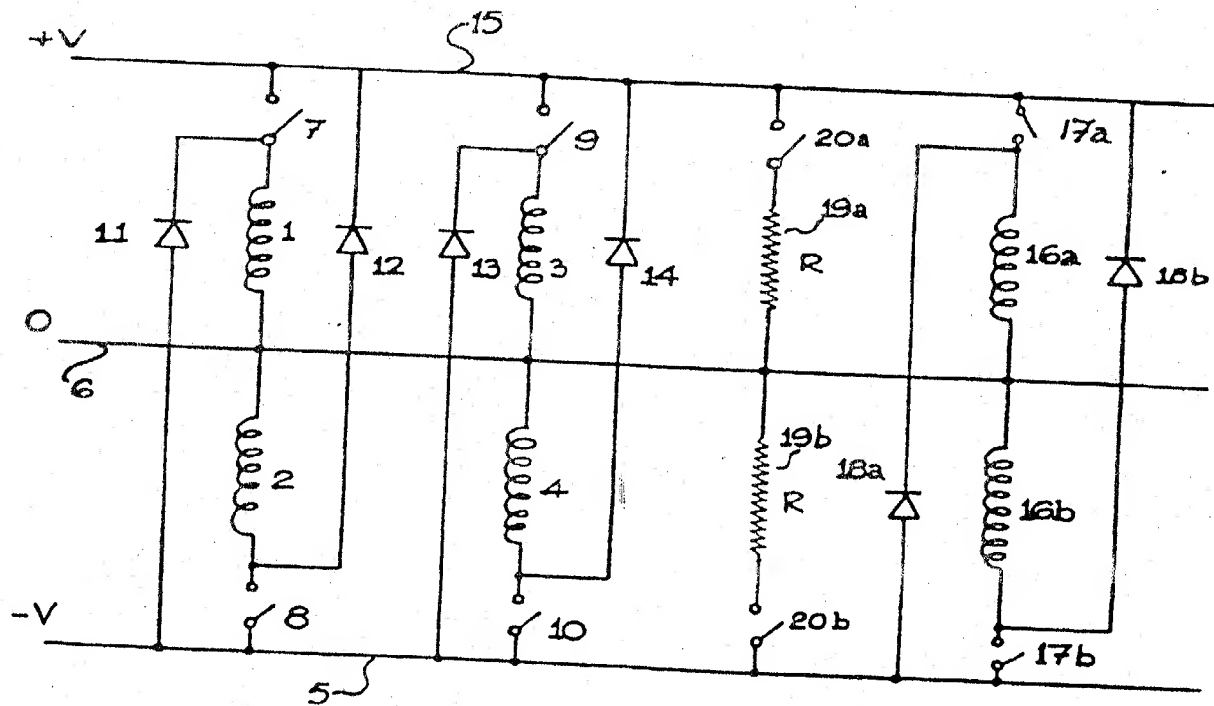


FIG. 3

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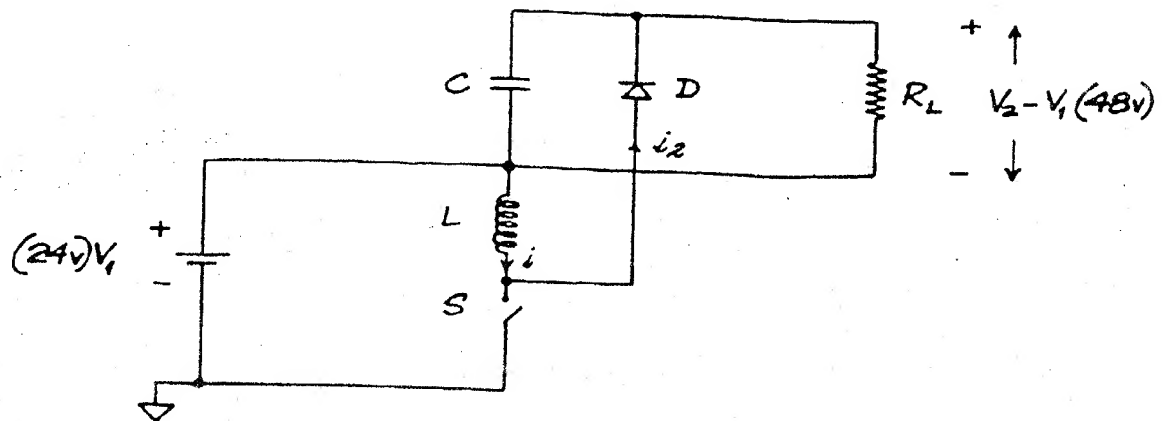


FIG. 4

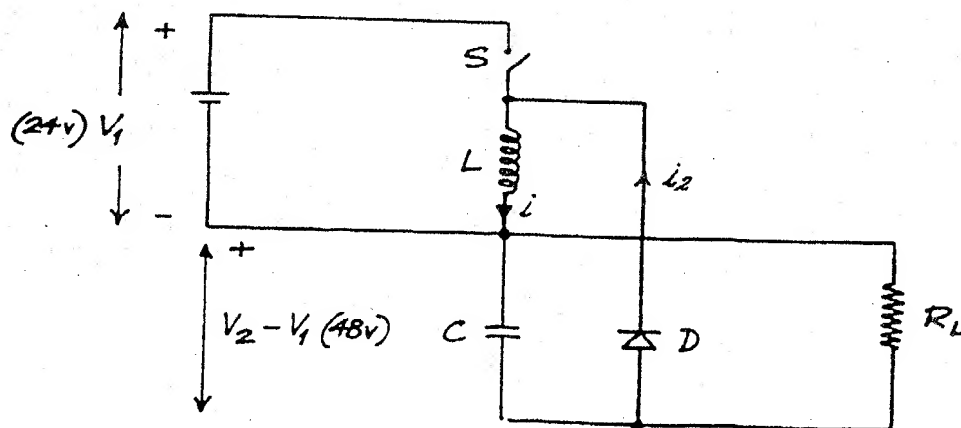


FIG. 5

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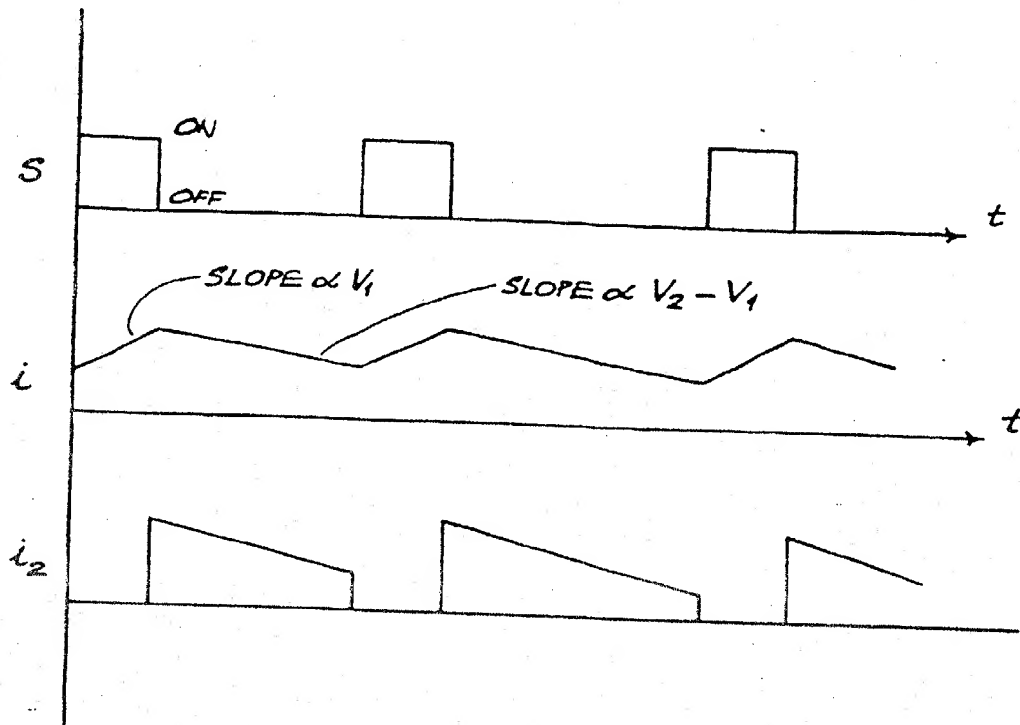


FIG. 6

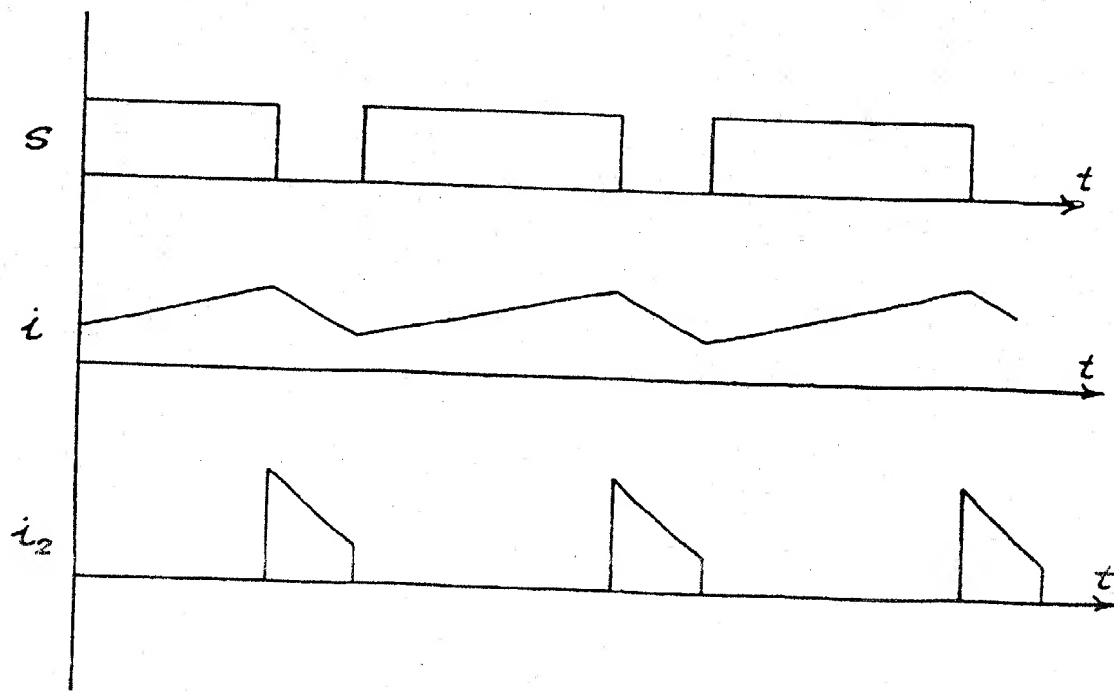


FIG. 7

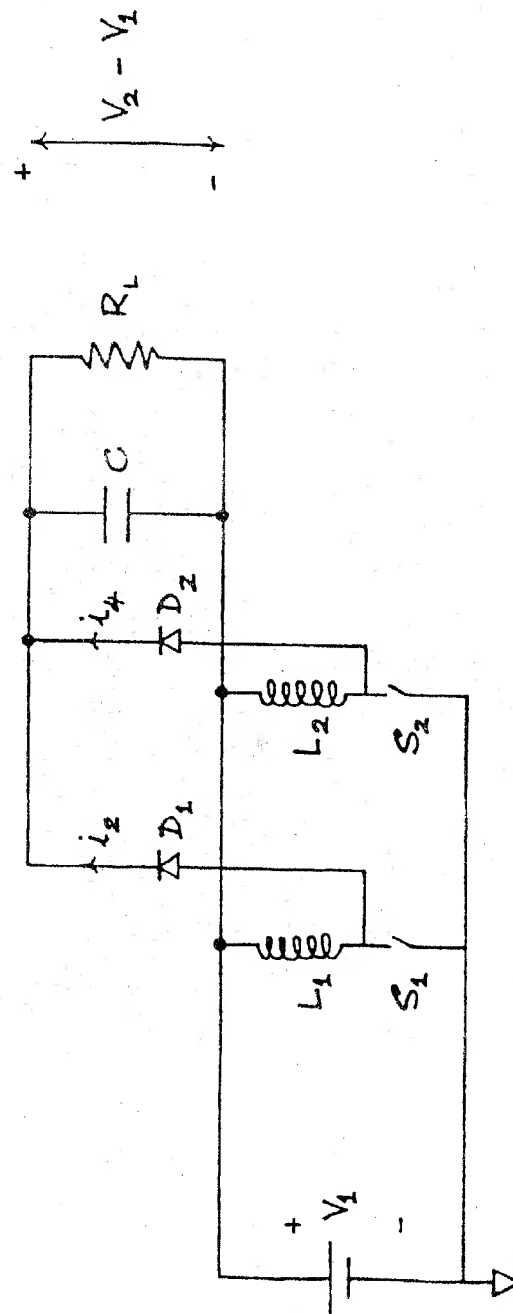
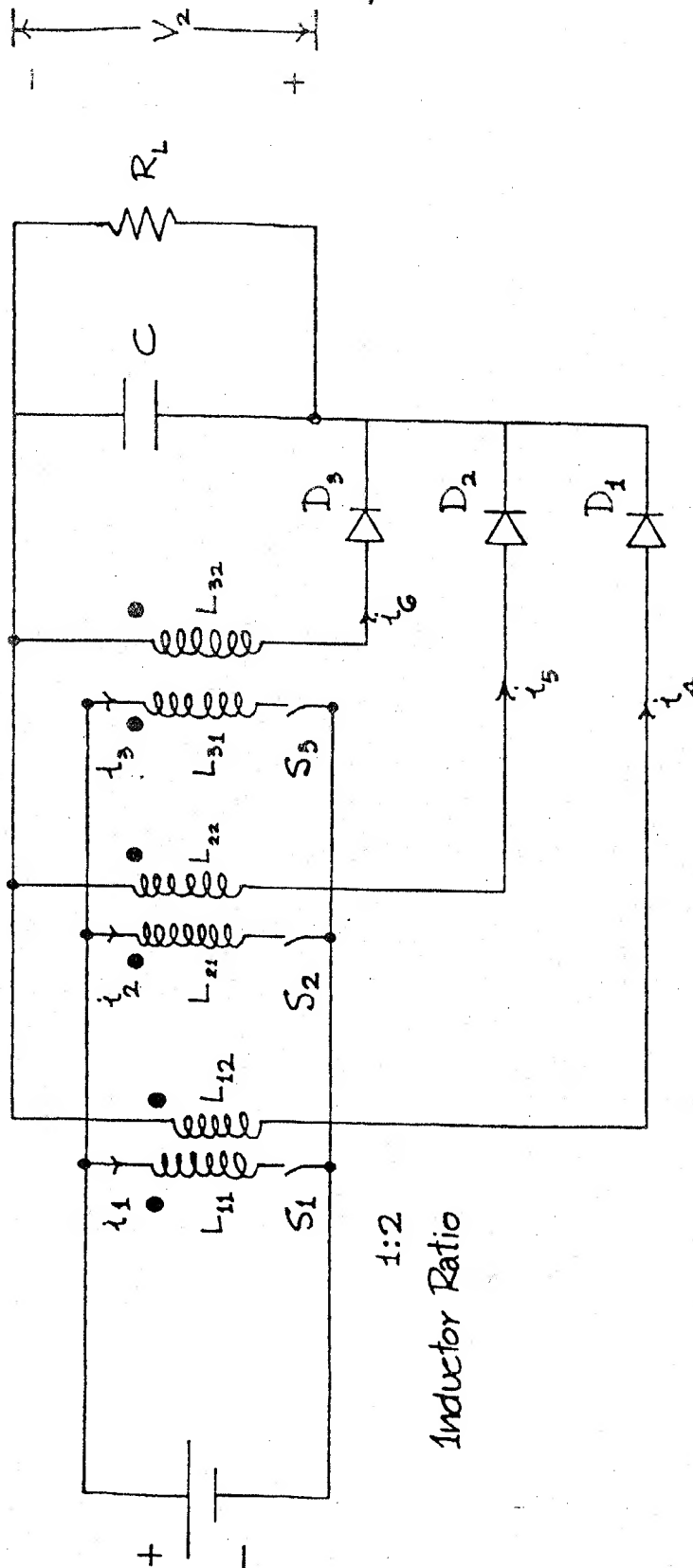


FIG. 8

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1:2
Inductor Ratio

FIG. 9

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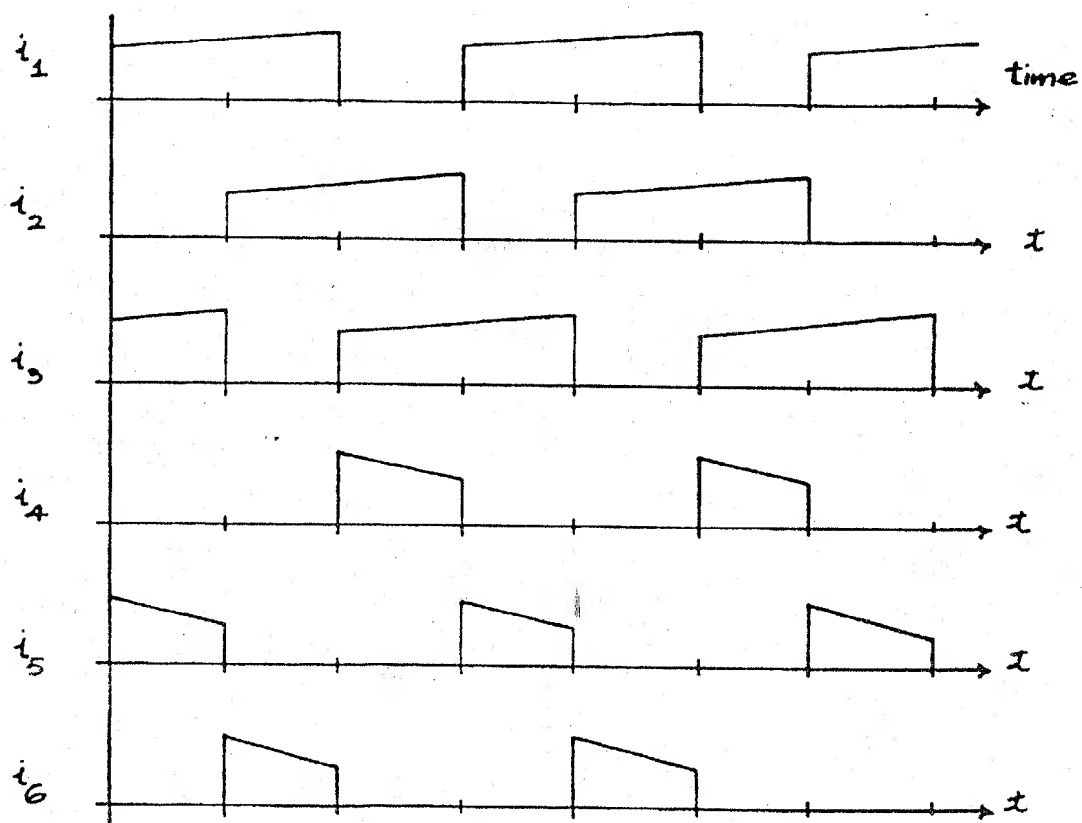


FIG. 10



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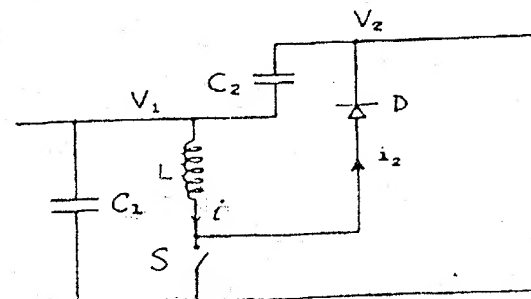
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EUROPEAN SEARCH REPORT

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DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 4)
X	DE-B-2 814 706 (MARCONI) * column 1, line 49 - column 2, line 2 *	1, 2, 5-7	H 02 M 3/335 H 02 P 6/02
X	US-A-3 913 000 (G.I. CARDWELL) * column 2, line 64 - column 3, line 30 *	1, 2, 5-7	
X	DE-A-2 538 835 (HITACHI) * page 8, last paragraph - page 9, last paragraph *	1, 2, 5-7	
X	DE-A-3 233 248 (LICENTIA) * page 5, paragraph 2 - page 6, paragraph 1; figure 1 *	1, 6	TECHNICAL FIELDS SEARCHED (Int. Cl. 4)
X	IBM TECHNICAL DISCLOSURE BULLETIN, vol. 23, no. 2, July 1980, pages 494, 495; M.B. BHUTA et al.: "Multiplexed flyback charging technique" * complete document *	1, 6	H 02 J 1/00 H 02 K 29/00 H 02 M 3/00 H 02 P 6/00 H 02 P 7/00
A	AT-B- 343 226 (ELIN-UNION) * page 2, lines 18-24 *	1	
The present search report has been drawn up for all claims			
Place of search BERLIN		Date of completion of the search 31-03-1987	Examiner GESSNER E A F
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DOCUMENTS CONSIDERED TO BE RELEVANT			Page 2
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 4)
A	US-A-3 829 749 (H. RICHT) * complete document * -----	1	
			TECHNICAL FIELDS SEARCHED (Int. Cl. 4)
The present search report has been drawn up for all claims			
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